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Analysis of the hydration heat evolution in cements incorporating construction waste powders by examining phase changes

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Abstract:

Construction and deconstruction activities generate significant waste, a large portion of which is recycled as coarse aggregates or sand. However, the fine fraction of this waste has the potential to be valorized as a sustainable substitute for cement. This study aims to evaluate the hydration behavior of construction waste powders (CWP), specifically, recycled ceramic powder (RCP), recycled brick powder (RBP), and recycled concrete powder (RCP), within eco-friendly mortars designed for enhanced efficiency and a reduced environmental footprint. These powders were used to replace 10%, 20%, and 30% of the cement by mass in mortar formulations to assess their influence on the heat of hydration. The results indicate that the waste powders exhibit cementitious properties, imparting mortars with favorable performance. The total heat released was reduced by up to 45%, and the peak hydration was delayed by 2–3 hours. This reduction in heat and retarded reaction is particularly beneficial for concreting in hot climates. Furthermore, while the nucleation and growth (NG) process was prolonged by brick (RBP) and concrete (RCP) powders, it was shortened by ceramic (RMP) powder. Conversely, mixtures incorporating RMP exhibited a more pronounced diffusion-dominated process compared to other mixtures.

Key words: Construction waste, diffusion, hydration heat, mortar, nucleation, phase change, powder, recycled concrete

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1. Introduction

Although construction waste is commonly recycled as aggregates for the manufacture of new concrete, its fine fraction often remains underutilized. Recycling this fraction as a partial replacement for cement is an effective strategy to reduce CO₂ emissions from cement production, preserve landfill space and improve the environmental sustainability of the construction sector [1, 2].

The contribution of CWP particles to hydration of cementitious materials is commonly assessed by monitoring the heat release. Notably, recycled concrete powder (RCP) contains fine fractions of anhydrous products, resulting in a more pronounced rehydration effect than other CWPs. This was evident in pastes containing 30% RCP, which exhibited a higher cumulative heat than plain Portland cement during the initial 13 hours. After three days, this heat of hydration reached 94.5% and 71.4% of that of ordinary cement paste for fine and coarse recycled concrete respectively [3]. Similarly, after 3 days of hydration, the cumulative heat released by cement containing 30% RBP decreased by 15% [4]. This reduction in heat is attributed to a dilution effect. However, the reaction kinetics were accelerated; the degrees of hydration at 24 h and 72 h for the pure paste were 30.74% and 37.86%, respectively, but increased to 37.56% and 53.99% after the introduction of 30% fine RBP [4]. Other results [5] show that RBP significantly increases the heat release during the initial reaction stage. For instance, the cumulative heat of a paste containing 45% RBP reached 14 J/g within two hours, a value 24% higher than that of the reference paste. Despite this initial acceleration, incorporating RBP generally weakens the overall heat flow, and the main peak value decreases as the RBP dosage increases, primarily due to the dilution effect. The main heat flow peak is closely associated with structural development at a very early age, as its appearance reflects the kinetics of the hardening process. Jia et al. [5] showed that the main peak of blended pastes appears earlier, occurring at 9.21 hours for the reference paste and 8.84 hours for the paste containing 45% RBP. However, when 30% of the cement was replaced by RBP, the maximum heat flux decreased from 2.44 J/g.h to 1.96 J/g.h and occurred 1.06 hours later. In a separate study, Du et al. [3] compared the variations in C-S-H contents between raw RCP and hydrated RCP pastes. They found that the initial C-S-H content was 34.4%, which increased to 46.1% and 48.3% after 3 and 28 days of curing, respectively. From this data, it can be inferred that 13.9% of the total C-S-H was generated from the rehydration of RCP, representing approximately 38.8% of the C-S-H content found in the raw RCP.

The formation of C-S-H hydrates, which are primarily responsible for the strength development in cementitious materials, is strongly influenced by the incorporation of powders as cement

replacements. While this substitution reduces the amount of cement clinker, often leading to reduced concrete strength [6], the properties of the powder are critical. Due to its finer particle size and higher pozzolanic activity compared to RCP, RBP-based concrete contributes to a denser microstructure and a more enhanced hydration reaction. This results in concrete with superior mechanical resistance. The influence of carbonate powder substitutions (RCP) on compressive strength can be complex; one study [7] reported an initial increase followed by a decrease (with values ranging from 2.27 MPa to 4.47 MPa at 28 days), attributed to the accelerated hydration caused by a slight increase in calcite content. Thermogravimetric analysis (TGA) of paste hardened for 28 days shows that the amount of C-S-H gel, the main hydration product, increases at a 20% substitution rate of carbonated RCP powder but decreases continuously at higher contents [4]. Furthermore, the derivative thermogravimetry (DTG) curve indicates that the rate of calcite decomposition between 650°C and 760°C is significantly faster in mixtures containing carbonated RCP than in the control mixture. This rate reaches its maximum at a dosage of approximately 60% [4]. In a separate study [8], the Ca(OH)_2 content of ordinary cement paste at seven days was 9.85%. With the incorporation of 10%, 20%, 30%, and 40% RMP, this content decreased by 12.59%, 18.78%, 29.04%, and 34.01%, respectively. By 56 days, the Ca(OH)_2 content in the RMP mixtures had decreased by 13.4%, 34.0%, 49.7%, and 56.6% for the same replacement levels. This overall reduction is primarily attributed to the dilution effect caused by replacing cement with RMP; consequently, a higher RMP content results in a lower portlandite (lime) content. The observed decrease in Ca(OH)_2 between 28 and 56 days is likely due to a pozzolanic reaction, wherein the RMP consumes portlandite to form secondary hydration products [8]. In addition, an analysis highlighted that the control mortar presents the highest weight loss of Aft and C-S-H gels evaluated at 5.02%, while the samples containing 20% and 40% of the RBP powder present a lower mass losses of 3.83%, 3.32% respectively. While the low reactivity of RBP at a very early age can lead to a reduction in hydration products [9], its fine particles can also accelerate the hydration of Portland cement through several mechanisms. First, they provide nucleation sites for the crystallization of hydration products. Second, they improve the packing density of the mixture, which increases the effective water-to-cement ratio by making more free water available for hydration. This increased water availability and the greater surface area for cement-water contact enhance the reaction kinetics. Notably, studies have documented an increase in lime (Ca(OH)_2) production within 24 hours due to these effects [9].

Monitoring cement hydration heat release allows control over the rate of hydration product formation and the early-stage processes governing this phenomenon. This concern has led to the development of hydration kinetics models based on nucleation and growth phenomena after contact

of the cement with the mixing water. When a new nucleation site forms in the solution, it attracts reactants and initiates growth. Sustaining nucleation conditions (space and reactants) enables hydration control via phase boundaries. The growing volume of hydration products restricts reactant mobility, making their supply diffusion-controlled [5, 10].

This work aims to study the hydration rate of an eco-plastic mortar composed of cement, natural sand and CWP as a substitute for cement. This waste consists of fine fractions of RMP, RBP and RCP replacing 0%, 10%, 20% and 30% in volume of cement. The research aims to quantify the effect of these CWPs on the hydration of the mixture by quantifying the heat released and its evolution over time. The results are subjected to modeling to determine the ultimate heat, the age to reach 50% of its value as well as the duration of the different hydration process. The experimental protocol implemented highlights all the equipment and materials used as well as the technical approach adopted to achieve this objective.

2. Materials and methods

2.1. Materials used

In this work, CEM II A-L 42.5 N composite cement was used. This cement is used to formulate a sand-based mortar standardized according to EN 196-1 standard [11]. It contains 12% limestone powder and has a compressive strength at 28 days greater than 42.5 MPa. Its Blaine specific surface is 3200 cm²/g. Its chemical characteristics are presented in Table 1. Natural sand of class 0/4 mm from the Cheliff River was used. Fig. 1 shows the particle size distribution of its grains and Table 2 summarizes its physical characteristics. The mixtures were mixed with drinking water. To achieve the required mortar consistency, a polycarboxylate superplasticizer was used. It significantly improves the rheological and mechanical properties of the cement paste and allows the production of plastic mortar with a low W/C ratio. It is compatible with all types of cement with a dry extract content of 27.5%, a pH of 5.5 and a density of 1.01.

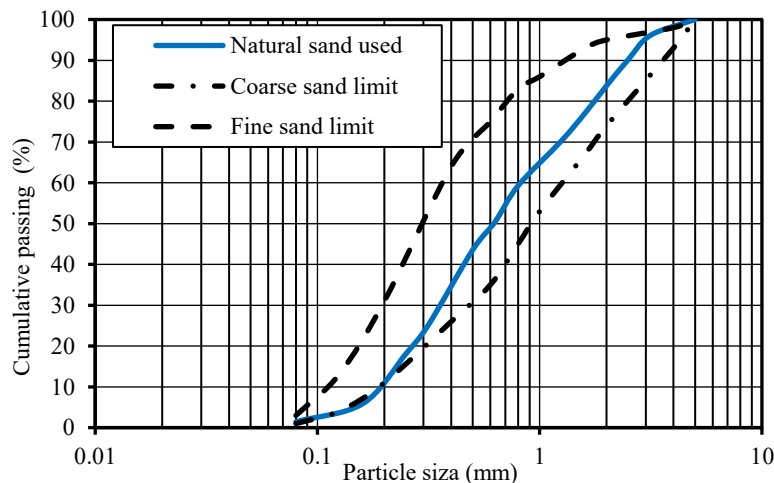


Fig. 1. Grading curve of natural sand used.**Table 1.** Chemical and physical properties of materials used.

Properties	Chemical composition (%)									Physical properties		
Materials	SiO ₂	Al ₂ O ₃	FeO ₃	CaO	SO ₃	MgO	Na ₂ O	K ₂ O	LOI	SSB m ² /kg	d ₁₀₀	γ (kg/cm ³)
Cement	22.6	4.2	3.55	62.17	2.19	0.63	0.4	0.42	1.84	320	100 μm	3100
RMP	59.4	18.2	6.40	3.40	0.11	2.46	3.10	4.10	1.75	462	80 μm	2550
RBP	63.6	20.6	5.20	1.80	1.40	1.10	0.81	2.10	1.85	432	80 μm	2710
RCP	38.2	8.6	7.90	28.40	1.80	1.96	0.86	1.85	4.30	312	90 μm	2770

Table 2. Characteristics of the sand used.

Désignation	NS
Fineness modulus	2.53
Sand equivalent(%)	91
Bulk density (kg/m ³)	1615
Specific density(kg/m ³)	2588
Absorption coefficient (%)	1.85

2.2. Construction waste Powders

To better utilize construction and demolition waste as a cement substitute, three common materials- ceramic, brick, and concrete- were sourced from a public landfill. The waste was manually sorted and recycled through a process of crushing and grinding. First, it was processed in a disc crusher and then a ball mill until fineness comparable to cement was achieved as shown in Fig. 2.



Fig. 2. Steps followed to obtain fines from construction waste.

2.3. Mortars composition

A standardized mortar mix with composition of sand:cement:water of 3:1:0.5. Volumetric substitutions of cement at 0%, 10%, 20%, and 30% were made using fine particles derived from recycled ceramic, brick, and concrete waste. A suitable amount of superplasticizer was used to standardize consistency, and all mix designs are summarized in Table 3.

Table 3. Compositions of tested mortars.

Mortars	Sand (g)	Cement (g)	Fine Fraction waste			Water (g)	Superplasticizer (g)	Spreading (%)
			Recycled ceramic	Recycled brick	Recycled concrete			
M-0 (0%)	1350	450	0	0	0	221,6	4,5	64
M-RMP10	1350	405	37,0	0	0	221,6	4,5	75
M-RMP20	1350	360	74,0	0	0	221,6	4,5	78
M-RMP30	1350	315	111,1	0	0	221,6	4,5	80
M-RBP10	1350	405	0	39,3	0	221,6	4,5	75
M-RBP20	1350	360	0	78,7	0	221,6	4,5	78
M-RBP30	1350	315	0	118,0	0	221,6	4,5	80
M-RCP10	1350	405	0	0	40,2	221,6	4,5	70
M-RCP20	1350	360	0	0	80,4	221,6	4,5	66
M-RCP30	1350	315	0	0	120,6	221,6	4,5	70

2.4. Sample preparation

To obtain a plastic and homogeneous mortar, the mixing step has a great impact on its expected properties. After fixing the different dosages of the different constituents that make up the mortar, the mortar preparation steps were followed according to the EN 196-1 standard [11]. The mixing was carried out for duration of 4 minutes divided into 4 steps. The operating mode is provided in Table 4.

Table 4. Different stages of mixing mortar.

	Components	 Cement+sand+dust	 2/3 Water	 1/3 Water+SP	/
	Duration	1 min	1 min	1 min	1 min
	Vitesse	Slow	Slow	Slow	Faste

2.5. Testing methods

According to the EN 196-9 standard [12], calorimetric analysis allows the measurement of the heat released during cement hydration. The Langavant calorimeter is a semi-adiabatic box equipped with a thermometer and sensor to track temperature changes. The recorded temperature data was subsequently used to calculate the cumulative heat released and the heat rate over time. The standard's provided expression [12] defines the total heat released as the sum of the heating and the thermal loss as shown in the following expression.

$$q(t) = \frac{C}{m_c} \Delta\theta + \frac{1}{m_c} \int_0^t \alpha \Delta\theta dt \quad (1)$$

Where:

- m_c : mass of cement or binder used in the test
- $C(J/^\circ C)$: thermal capacity of the calorimeter and the test piece
- $\alpha (J/h.^\circ C)$: total heat loss coefficient of the calorimeter given by the calibration.
- $\Delta\theta$: heating of the test piece compared to the ambient temperature.

3. Results and discussions

3.1. Hydration heat

Most hydration reactions are accompanied by a release of heat which can be quantified to fully understand these reactions. The heat recorded by a calorimeter gives continuous release values which are suitable for estimating the hydration of this system composed of CWP and cement. Once the heating measurements have been carried out, the heat of hydration is evaluated by converting Equation 1 into an algebraic equation and introducing the different parameters of the test. The obtained results are illustrated in Figs. 3a, 4a and 5a. According to the obtained results, cements with different CWP rates present a continuous evolution hydration heat with close values during the first day. At 8 hours; all heat released is lower than that of the control except for the mortar with 10% RMP which generates a heat of 112 J/g against 109 J/g for the control mortar. This result indicates that RMP influences the early hydration of cement, which can be attributed to its finesse and its nucleation effect. After ten hours, all the heats of hydration released are lower than those emitted by the mortar without CWP.

At five days, the heat released by the hydration of ordinary cement reaches 298 J/g while it decreases to 285 J/g, 262 J/g and 223 J/g when the cement is substituted by 10%, 20% and 30% of CMP respectively. When the cement is substituted by RBP, the same substitution rates lead to a heat release of 255 J/g, 231 J/g and 192 J/g. The use of RCP leads to even lower heats of the order

of 251 J/g, 208 J/g and 169 J/g respectively. The results show that replacing ordinary cement with CWP reduces the hydration heat in order $M-0 > M-RMP > M-RBP > M-RCP$. It is noted that the heat of hydration of mortars when cement is replaced by 20% RMP, RBP or RCP is 88%, 77% and 70% of that of the control mortar. These results are consistent with those of Rocha and Filho [13] in which cement containing 30% RCP showed the greatest reduction in cumulative heat at 5 days of 21% compared to the reference. This result highlights a beneficial effect of these additions to counter the rise in temperature and make these mortars more effective in hot climates.

3.2. Heat flux of hydration

Using the results obtained from the heats of hydration, the released flux can be represented by a simple ratio between the heat increment and the corresponding time step. Figs. 3b, 4b and 5b illustrate the results obtained where the different hydration phases appear clearly. The first remark highlights the reduction in the second hydration peak. For 30% cement substituted with RMP, RBP and RCP, the peak heat flux is reduced from 24.5 J/g/h to 15.9 J/g/h, 13.5 J/g/h and 13.5 J/g/h respectively. The second observation consists of a prolongation of the thermal release with a delay in the appearance of the second peak of 2 to 3 hours. Ordinary cement exhibits a maximum heat flux that occurs after 5 hours of contact with mixing water, but it takes up to 8, 7 and 9 hours for it to occur when the cement contains 30% RMP, RBP or RCP respectively. This confirms the interest in combining ordinary cement with other additions, especially those from recycling.

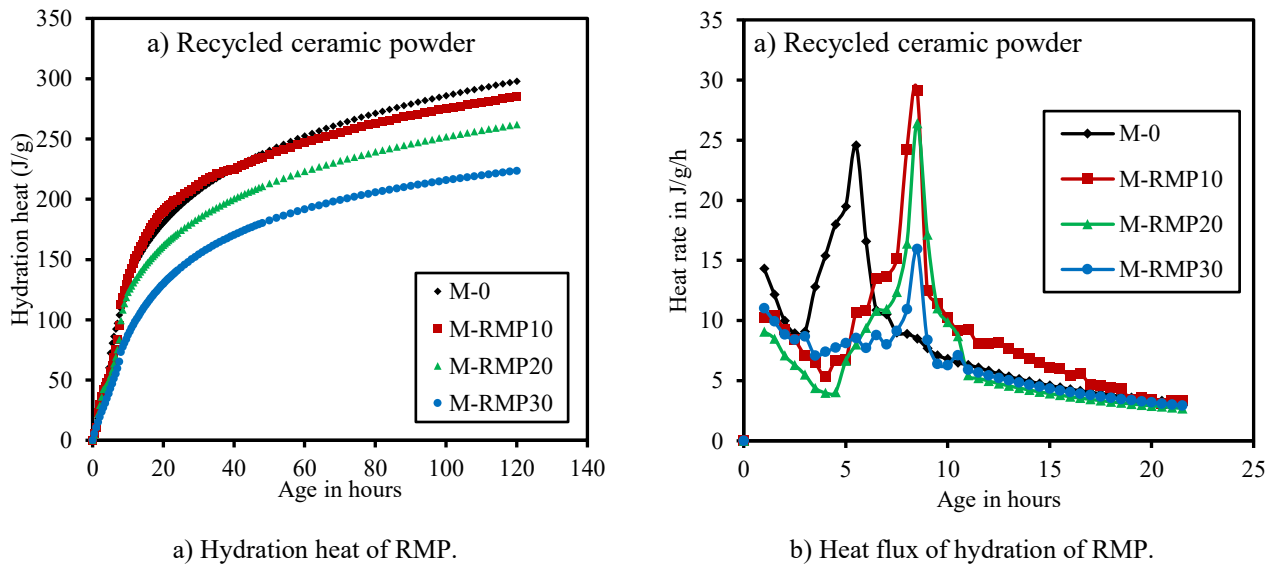


Fig. 3. Evolution of the heat of hydration and heat flux of hydration of mortars with different RMP contents.

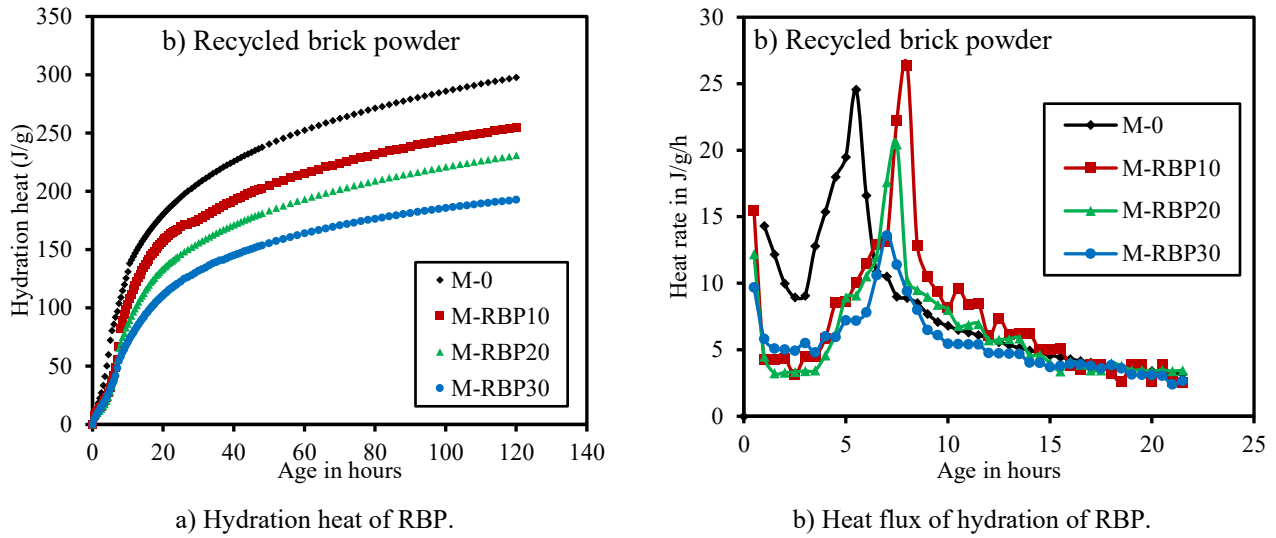


Fig. 4. Evolution of the heat of hydration and heat flux of hydration of mortars with different RBP contents.

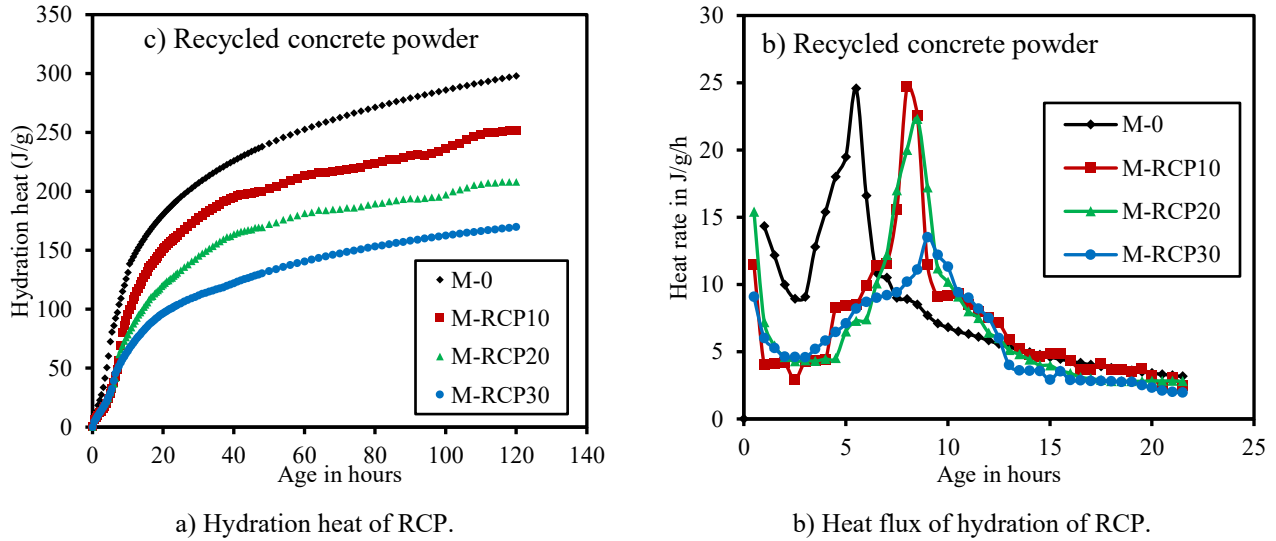


Fig. 5. Evolution of the heat of hydration and heat flux of hydration of mortars with different RMP contents.

3.3. Analyze of hydration heat results

To analyze the obtained results, an approach recommended by ASTM C1074-93 [14] to analyze some concrete properties development under isothermal curing was used. It was assumed that the kinetics of the concrete properties at a constant temperature can be represented by the following hyperbolic equation.

$$X(t) = X_u \frac{t - t_0}{(t - t_0) + t_{50}} \quad (2)$$

Where $X(t)$ is the concrete property at t age; X_u is the ultimate property value at long term; t_0 is the age when the concrete property development is assumed to start and can be assumed to zero for hydration heat and compressive strength, and t_{50} is the age where the concrete property reaches 50% of its ultimate value. A least-squares regression analysis for Equation 2 was used to determine

the best-fit values of X_u and t_{50} for each set of data [15, 16]. The value of t_0 simulating the start of the heat release was taken equal to zero because the test was started immediately after mixing.

The correlation of the results of hydration heat according to Equation 2 gives the values of the age t_{50} and the ultimate property values Q_u for each mixture. Equation 2 parameters found are summarized in Table 5 with the root mean square error (RMSE) and the coefficient of determination (R^2) values corresponding to each mixture. The values R^2 are very close to unity and the RMSE values do not exceed 10 J/g. From this adjustment, it can be concluded that the behavior of the different mixtures leads to a drop in the ultimate heat of hydration released proportional to the substitution rates of cement by CWP. Fig. 6 illustrates a linear variation as a function of the CWP content. Additionally, the rate at which this heat is released becomes slower as the content of these powders increases. Only RMP powder records acceleration for rates close to 10%. Using Equation 2, other works have described the ultimate heats and half-ages of hydration by polynomial forms of the superplasticizer dosages [17]. With Equation 2, Djeddar et al. [18] proposed a relationship that highlights a combination effect of silica fume content and water/cement ratio to describe ultimate heats of hydration.

Table 5. Equation 2 parameters found for each mortar mixture according to hydration heat results.

	M-0	M-RMP10	M-RMP20	M-RMP30	M-RBP10	M-RBP20	M-RBP30	M-RCP10	M-RCP20	M-RCP30
Q_u (J/g)	329	303	284	260	291	269	227	289	244	195
t_{50} (hours)	16,8	14,4	16,1	20,6	19,3	22,1	22,2	20,5	21,4	21,7
RMSE (J/g)	5,96	4,0	3,01	2,66	9,40	6,69	3,61	9,72	5,25	3,45
R^2	0,994	0,997	0,998	0,998	0,984	0,991	0,996	0,984	0,993	0,994

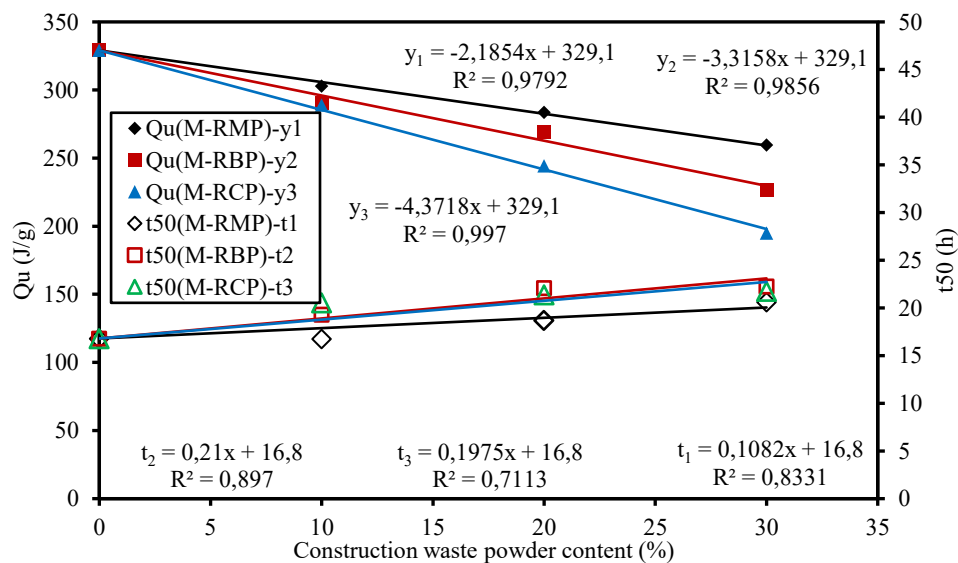


Fig. 6. Variation of parameters of Equation 2 as a function of CWP content for heat of hydration results.

3.4. Kinetics of phase change to understand the heat of hydration

Previous studies [19, 20, 21, 22] have shown that cement hydration kinetics consist of three main processes based on nucleation and crystallization growth (NG), interactions at phase boundaries (I) and diffusion (D). Nucleation is the initial process of formation of microscopic nuclei by cement ions dissolved in the pore solution. The assembly of these ions forms stable clusters that become the nucleation sites for newly formed hydrates. The hydration products grow and organize into well-defined crystals. The growth of these hydrates is influenced by the interface boundaries between the cement grains and these hydration products. This interaction at the phase boundaries influences pore distribution, density, solid-phase connectivity, and mechanical strength. Diffusion is a physicochemical process that controls the transport of dissolved cement ions in the forming cement paste. The ions move by diffusion from the rich zones near the dissolving grains to the precipitation sites where new hydration products form.

The hydration kinetics describes the progress of the chemical reaction of a complex system composed of several minerals constituting the cement and the mineral additions. It can be described by the degree of hydration expressed at a time t by the ratio between the heat released $Q(t)$ on the ultimate heat Q_u .

$$\alpha(t) = \frac{Q(t)}{Q_u} \quad (3)$$

Basic equations were proposed by Avrami [19] and developed by several researchers [20, 21, 22] to describe these three hydration process as a function of the degree of hydration and which are expressed as follows:

$$[-\ln(1 - \alpha)]^{1/n} = k_{NG} t \quad (4)$$

$$1 - (1 - \alpha)^{1/3} = k_I t \quad (5)$$

$$[1 - (1 - \alpha)^{1/3}]^2 = k_D t \quad (6)$$

The value of n describes the geometric crystal growth and its value takes generally 1, 2 or 3 for needle, plane or isotropic growth, respectively [10, 23]. The values k_{NG} , k_I , k_D are kinetic constants that can be determined graphically by fitting the above equations with linear lines. These fundamental equations describing the hydration kinetics during the dominant nucleation and growth process are often used for spherical particles. In this analysis, the radius of the cement grains is not

taken into account so the coefficients k remain unchanged as suggested by Krstulovic and Dabic [24], which allows obtaining new equations for each process describing the heat rate of hydration:

$$\left[\frac{d\alpha}{dt}\right]_{NG} = k_{NG} n (1 - \alpha) (-\ln(1 - \alpha))^{\frac{n-1}{n}} \quad (7)$$

$$\left[\frac{d\alpha}{dt}\right]_I = 3 k_I (1 - \alpha)^{\frac{2}{3}} \quad (8)$$

$$\left[\frac{d\alpha}{dt}\right]_D = \frac{3}{2} k_D \frac{(1-\alpha)^{\frac{2}{3}}}{1-(1-\alpha)^{\frac{1}{3}}} \quad (9)$$

From the experimental results obtained in the first part, the degree of hydration of each mortar is calculated as a function of time. The kinetic analysis of hydration of cement containing CWP is based on the previously mentioned model, which encompasses the three dominant processes of this phenomenon, namely: NG, I and D. By linearizing equations 4, 5 and 6, the results are obtained and grouped in Table 6. The kinetic parameters found make it possible to observe differences in hydration of ordinary cement mortar and when contain some recycled construction powders [24].

According to these results, the coefficient n is just above unity, indicating an angular shape of the cement grains. The value of exponent n value is higher in the case of ordinary cement and is reduced by 16%, 12% and 10% when cement contains 10% RMP, RBP and RCP respectively. As reported by Han et al. [25], it was found that n value decreases with increasing slag content and increases with increasing temperature. As the CWP rate used is relatively low, the nucleation phase is significantly improved, especially for RBP and RCP. This is consistent with the results of Han et al. [25] where a small amount of blast furnace slag improves the water/cement ratio and promotes the nucleation of hydration products. The kinetic constants k_I and k_D are lower in the presence of CWP caused by the extension of the time required for hydration products to reach supersaturation. Therefore, the hydration rate of the composite binder containing more CWP is lower, especially in process I. Cements containing RMPs exhibit resistance to the diffusion of ions and water, resulting in a very low kinematic coefficient and a longer D phase than other cements. This result has already been confirmed in other work [26] by comparing the hydration of cement containing 50% slag with another containing 50% fly ash.

Also, it is evident that higher CWP content leads to a reduction in all kinetic parameter values. It is clear that lower Portland cement content leads to fewer hydration products, prolonged supersaturation time, and reduced activation of CWPs. The coefficient k_{NG} is four times higher than that of k_I and 25 to 45 times higher than that of k_D . This observation aligns with other findings [26], who reported that the NG process occurs significantly faster than I and D processes. Also similar

result [27] was reported in which the value of constant k_{NG} was 3–5 times k_I and 10–30 times k_D . The mentioned study reported that 50% fly ash reduced the hydration rate constants, degree of hydration and hydration mechanism constants of Portland cement by 44%, 33% and 19%, respectively.

Table 6. Kinetics parameters of hydration process of cement with various CWP.

Sample	n	k_{NG}	k_I	k_D
M0	1,3059	0,0635	0,0155	0,0014
M-RMP10	1,0889	0,0540	0,0139	0,0012
M-RMP20	1,1213	0,0510	0,0140	0,0011
M-RMP30	1,0742	0,0424	0,0121	0,0010
M-RBP10	1,1520	0,0434	0,0115	0,0016
M-RBP20	1,1213	0,0366	0,0107	0,0014
M-RBP30	1,1100	0,0309	0,0085	0,0010
M-RCP10	1,1717	0,0375	0,0102	0,0012
M-RCP20	1,1610	0,0386	0,0100	0,0013
M-RCP30	1,1460	0,0424	0,0110	0,0014

Fig. 7 illustrates the 24-hour hydration rate of cements blended with 10% CWP, including experimental results and simulations based on Equations 7, 8, and 9. The durations of the distinct phases can be determined graphically from the intersection points of the curves generated by the three equations, as demonstrated in previous work [27]. For all blends, the results indicate that the process begins with nucleation and crystallization growth, followed by a short period of interactions at phase boundaries and ends with prolonged diffusion phase.

Nucleation and crystal growth (NG) → Interactions at phase boundaries (I) → Diffusion (D)

Upon initial contact between cement and mixing water, the interstitial solution becomes saturated with reactive products, leading to the formation of numerous nucleation sites around preferred grains. As the matrix densifies, ionic mobility is hindered, promoting boundaries interactions. Once ionic movement ceases entirely, ion diffusion becomes the sole mechanism for completing hydration.

Fig. 8 shows the time taken by each process during the hydration of the different cements. It should be noted that determining the duration of nucleation and crystal growth is difficult to measure, and the interference between the various processes makes their separation challenging. From these results, the NG process is highly pronounced in the presence of 20% RBP and 10% RCP. This

finding aligns with Thomas results [28], which show that the NG process initiates at the initial contact with mixing water, indicating that the induction period is not a separate chemical process.

The I process is stronger when the cement contains more than 10% RBP or 10% RCP. The cement with RMP exhibits a more significant diffusion process compared to the other cements. Thus, it appears that cement hydration is strongly influenced by the presence of RBP and RCP. The use of RMP shortens the NG phase, while RCP prolongs it, both remaining within the range of the induction period, as shown in Fig. 8. It is evident that the fineness of the cement accelerates its reactivity with water, as is the case with the presence of RMP powder. This finding aligns with other result [29] showing that when the fineness of cement slag increases, the NG and I processes gradually shorten, while the D process gradually lengthens.

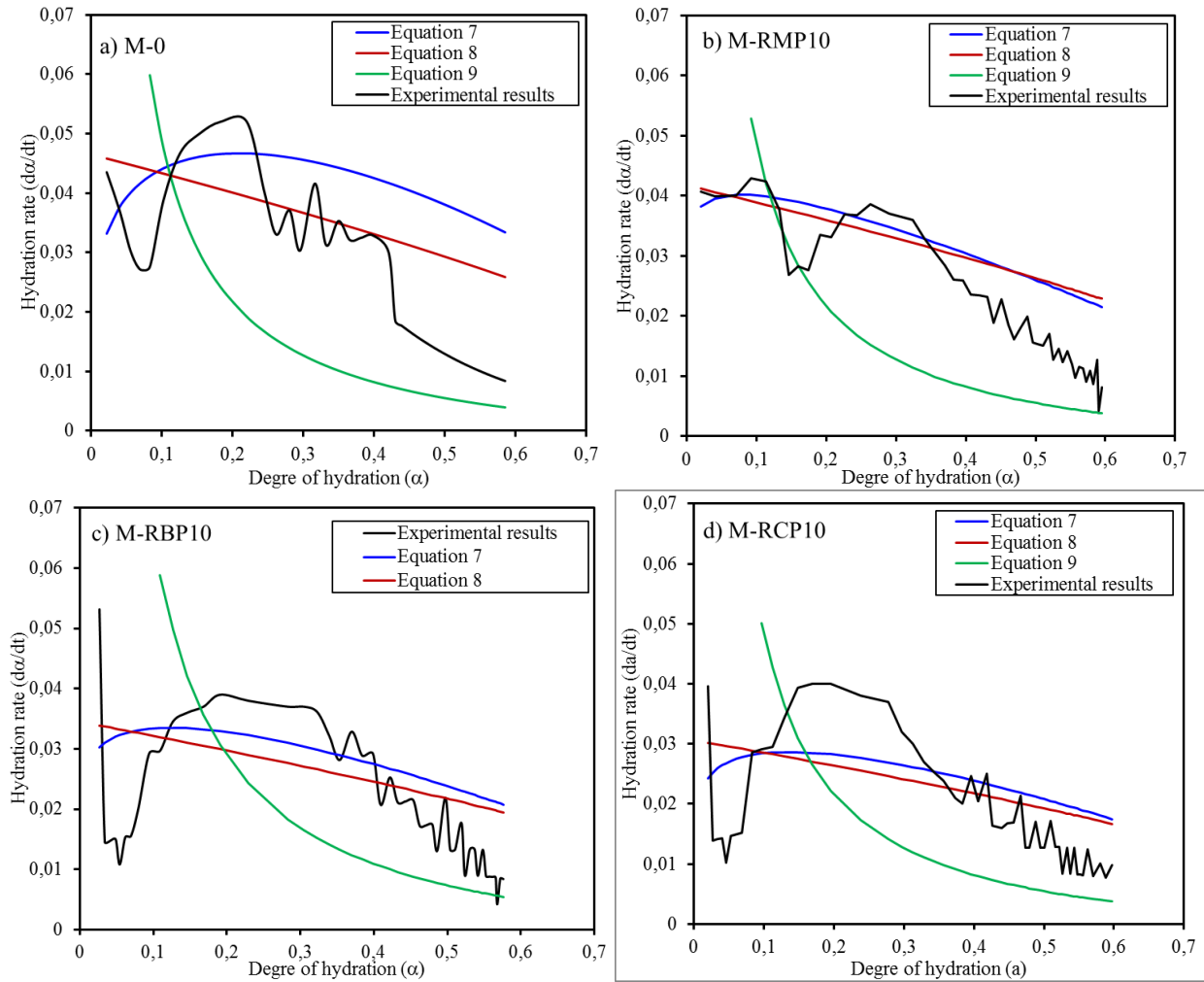


Fig. 7. Modeling and experimental results of hydration rate according to the degree of hydration during the first 24 hours.

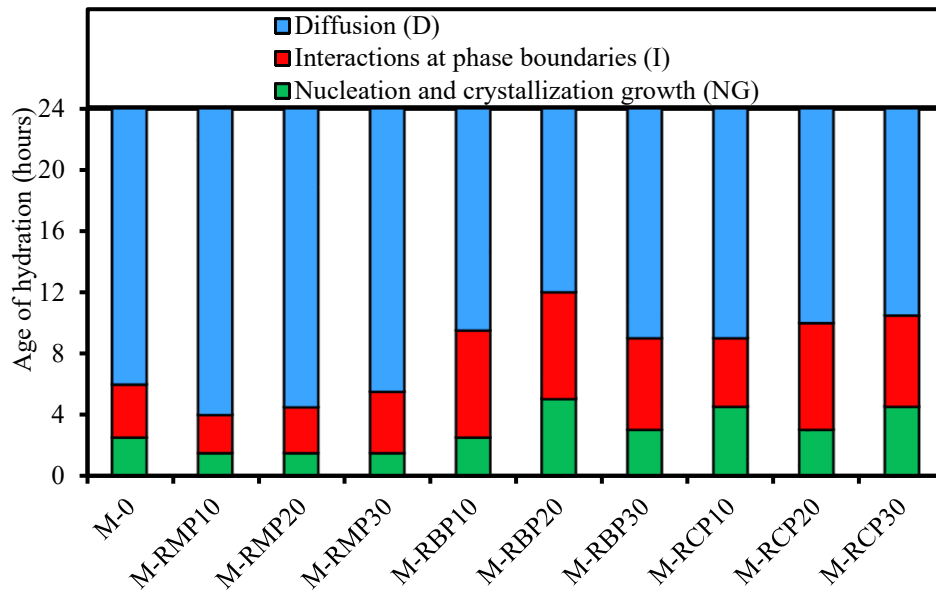


Fig. 8. Duration of domination of each individual process during the first 24 hours of hydration.

4. Conclusions

Portland cement is a material whose production has a significant environmental impact and a significant consumption of natural resources. Construction and demolition waste also represents very large quantities of fine materials with no possibility of reuse. Depending on their origin and fine fractions, CWP's present a very significant variability in terms of composition, physical and/or chemical properties. However, cement production represents a major opportunity for the recovery of several types of this waste, particularly as a substitute raw material in cement production. Following this experimental study, certain conclusions can be drawn:

- The waste used (ceramic, brick, concrete) are considered as mineral materials with a hardness similar to that of clinker allowing them to be introduced as supplementary cementitious materials in cement plants.
- At five days, the heat of hydration for cements containing 20% RMP, RBP or RCP represents 88%, 77% and 70% of that of ordinary cement. This shows a beneficial effect of these additions to combat the rise in temperature and make these mortars more efficient in hot climates.
- From the obtained heat flux, the different hydration phases appear clearly. First, the value of the main peak increases for a substitution rate of 10% and decreases significantly for a substitution rate of 30%. Second, these main peaks are delayed by 2 to 3 hours. Third, the dormant period is prolonged.

- Hydration kinetics is delayed with each increase in the recycled powder rate. For each 10% substitution rate, heat release is delayed by 1 hour for RMP and by two hours for RBP and RCP.
- The nucleation and crystal growth processes is stronger in the case of ordinary cement and weakest when RMP powder is added. The coefficient k_{NG} is four times higher than that of k_I and 25 to 45 times higher than that of k_D .
- The NG process is highly pronounced in the presence of 20% RBP and 10% RCP
- The I process is stronger when the cement contains more than 10% RBP or RCP.
- The cement with RMP exhibits a more significant diffusion process compared to the other cements.

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